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Development and evaluation of an automated system for testing current meters

Ezequiel Saretta[1], Antonio P. de Camargo[1], Tarlei A. Botrel[1], Marinaldo F. Pinto[2], Geancarlo T. Katsurayama[1] & José A. Frizone[1]

[1] Universidade de São Paulo/Escola Superior de Agricultura "Luiz de Queiroz"/Departamento de Engenharia de Biossistemas. Piracicaba, SP. E-mail: saretta@usp.br (Corresponding author); apcpires@usp.br; tabotrel@usp.br; katsurayama@usp.br; frizzone@usp.br
[2] Universidade Federal Rural do Rio de Janeiro. Seropédica, RJ. E-mail: mfpufrrj@yahoo.com.br

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ABSTRACT

Current meters are equipment widely used for estimating flow velocity in rivers and streams. Periodic calibrations of current meters are important to ensure the quality of measurements, but the required testing facilities are complex and only available in a few institutions. However, advances in electronics and automation may contribute to developing simple and reliable calibration systems. Thus, this study aimed to develop an automated system for testing current meters, which consisted of a trapezoidal channel, a step motor, a tow car and a management system, composed of a supervisory application and microprocessed modules to control the motor and the data acquisition. Evaluations of the displacement velocity showed that it matched the reference value up to 1.85 m s^{-1} for a vertical-axis current meter and 2.3 m s^{-1} for a horizontal-axis one. The developed system showed reliability during tests, for both current meter movement and data acquisition. The management of the system based on the developed modules and the supervisory application improved its user interface, turning all the procedure into a simple task.

Palavras-chave:
hidrometria
eletrônica
automação
calibração

Desenvolvimento e avaliação de um sistema automatizado para ensaios de molinetes

RESUMO

Molinetes são equipamentos amplamente utilizados para estimativa da velocidade da água em cursos d'água. A calibração periódica de molinetes é necessária para assegurar a qualidade das medições mesmo requerendo infraestrutura complexa para ensaios dos quais poucas instituições dispõem; contudo, os avanços em eletrônica e automação podem contribuir para desenvolver sistemas de calibração simples e confiáveis; assim, desenvolveu-se um sistema automatizado para ensaios de molinetes formados por um canal trapezoidal, motor de passo, carro de reboque e um sistema de gerenciamento composto por aplicativo supervisório e módulos microprocessado para controle do motor e aquisição de dados do molinete. Avaliações da velocidade de deslocamento mostraram correspondência com valor de referência até 1,85 m s^{-1} para um molinete de eixo vertical e 2,3 m s^{-1} para um de eixo horizontal. O sistema desenvolvido apresentou confiabilidade na execução dos ensaios tanto na movimentação do molinete quanto na aquisição de dados. O gerenciamento do sistema por meio dos módulos desenvolvidos e do aplicativo supervisório facilitou sua utilização por parte do usuário tornando a rotina de calibração bastante simples.

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Introduction

Velocity-area is the most popular method for flow estimation in water streams, consisting of a discrete integration of velocity, along the cross-section of the channel (Clemmens & Wahlin, 2006; Le Coz et al., 2012; Cohn et al., 2013). Despite the amount of equipment and available technology, current meters are still the widely used devices in various engineering applications, because of the stability and reliability of their measurements (Camnasio & Orsi, 2011). This measuring instrument estimates water velocity at a specific point of the section, usually through a linear equation relating it to the propeller rotation velocity.

The quality of current meter measurements is guaranteed by periodic calibrations, since, over time, its use can modify the calibration equation (Camnasio & Orsi, 2011). USDI (2001) suggest that current meters must be gauged every 100 h of use or, at least, once a year. Calibrations are performed in a straight open channel with still water. The current meter is fixed to a tow car and moved in uniform rectilinear motion along the channel at different velocities, recording both the displacement velocity and its rotation velocity (De Doncker et al., 2008). Ultimately, the calibration coefficients are obtained through linear regression analysis.

ISO (2007) describes the standard method for current meter calibration in straight open channel, for which the greatest difficulty is probably the need for a structure of tests, which must be assembled in a channel dedicated only to this purpose and long enough to allow testing specific ranges of displacement velocity. On the other hand, some tests with velocities lower than 1 m s^{-1} show lower precision (Engel, 1999). De Doncker et al. (2008) also reported higher precision of current meters for displacement velocities higher than 0.3 m s^{-1}. Therefore, the performance of current meters at low velocities (< 1.0 m s^{-1}) still seems to have remaining issues, in terms of reliability.

Instead of this calibration method in channels, an alternative method can be that in which the current meter propeller is fixed to a submerged nozzle or hole of a plate separating two reservoirs. Through the Torricelli equation, water velocity is calculated considering the pressure head as equal to the difference between the levels of upstream and downstream reservoirs. This method requires a simpler, less expensive structure compared with the standard method; however, Camnasio & Orsi (2011) concluded that a few improvements are necessary for it to be considered as an alternative method.

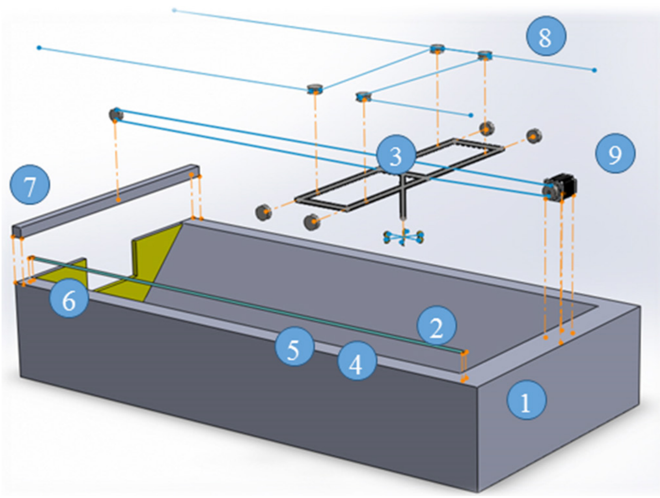
This study aimed to develop an automated testing system for the calibration of current meters based on the standard method cited by the ISO 3455 (ISO, 2007), allowing the calibration of these devices for a velocity range of up to 2 m s^{-1}. Microcontrollers and other technologies available for industrial use must be employed to automate the systems of control and data acquisition with reliability in the tests.

Material and Methods

The system was developed at the Laboratory of Hydraulics of the Department of Biosystems Engineering, at the "Luiz de Queiroz" College of Agriculture, in Piracicaba-SP, Brazil, built over a trapezoidal channel made of brickwork with 1:1 slope (Figure 1), upper base of 2.30 m, total depth of 0.70 m and length of 12 m. There was a rectangular spillway upstream the channel, which was used only to maintain a water depth for the immersion of the propeller during the tests. For the movement of the current meter, a tow car was built using steel tubes (width = 0.30 m; length = 2.20 m), which moved over the channel using nylon pulley wheels, guided by a rail on one of its sides (Figure 1). Besides the rail, an orthogonal system was used to avoid misalignment and guarantee an uniform linear motion of the tow car along the channel. For this, pulleys and steel cables were used to form two Z-shaped arrangements, one on each side of the car (Figure 1), similar to that used in rulers of technical drawing tables, maintaining it parallel to one of the sides of the table.

The tow car was moved using a traction system, which comprised a step motor, a driver and a Traction-Control Module (TCM). The motor was fixed upstream the channel using a driving pulley with diameter of 12.3 cm, which moved a steel cable attached to the tow car (Figure 1). Upstream of the channel, a support for the fixation of the steel cables of the orthogonal system and a pulley (diameter = 5 cm) were mounted, to guide the steel cable in the traction of the car.

One of the main advantages of the step motor, compared with other types of motors, is the control of position, i.e., its movement shows higher reliability. The motor used in the study required a voltage of 50 V d.c. and current of 7.8 A per phase, with eight coils individually activated in sequence; however, some control systems based on microprocessors generally operate with lower voltage and current, requiring a power driver. The driver also simplifies the controls of direction and rotation velocity of the motor through two analogical inputs of up to 24 V d.c. Clockwise direction is activated by maintaining its respective input high and counterclockwise is activated by maintaining it low. The rotation velocity is driven by the interval of pulses sent to the other input and is higher when the time is lower. These two analogical inputs of the driver were



1) Open channel; 2) Rail; 3) DAM; 4, 5 and 6) Reed switches; 7) Pulley support; 8) Orthogonality system; 9) Traction system

Figure 1. Workbench developed for the testing system (DAM - Data-acquisition module)

activated by tensions of 0 and 5 V d.c. from a microcontroller installed in the TCM electronic circuit.

System control was separated into three parts: TCM, for the control of the tow car movement, current meter Data-Acquisition Module (DAM) and a supervisory application. Both modules were connected to a computer, which controlled the routine of calibration of the current meters through the supervisory application; each module received, interpreted and responded only to the commands of the computer.

The TCM used a PIC16F876A microcontroller, connected to the computer through a RS-232 serial port, which controlled the motor direction and rotation velocity. The track along which the tow car moved was controlled by two magnetic reed switches, activated by magnets fixed to the tow car chassis. Each switch was placed at about 2 m distant from the end of the channel, signaling to the TCM the end of the track and allowing slowdown. Current meter data were collected only when the tow car moved from the motor towards the spillway.

Since each current meter model provides different hydrodynamic resistances, the TCM recorded the time necessary for the set to travel the distance of 5 m indicated by two auxiliary switches. The first one was placed at 5 m from the beginning of the channel, a distance necessary for the aceleration of the set, and the second one was the same switch signaling the end of the track. The time was measured by the TCM microcontroller, which has an internal timer with resolution of 1 ms, and sent to the application for the calculation of the displacement velocity, used to adjust the current equation.

The DAM was used to record the current meter rotation velocity and send the data to the supervisory application, which was equipped with hardware and software resources for acquisition, conditioning and processing of signals from the current meter, which consisted mostly of tension pulses at each revolution of the propeller, counted along the time for the calculation of rotation velocity. This module also consisted of an electronic circuit equipped with a PIC16F876A microcontroller, besides an Xbee-type radio frequency communication module, which facilitated the communication with the computer through radio frequency, since the DAM moved along with the current meter.

The supervisory application was responsible for providing a graphic interface between the modules and the user, as well as controlling the entire routine of current meter calibration. Thus, the user needed to select the velocity and start the system, which became autonomous in the movement of the current meter, through the TCM, and in its monitoring, through the DAM.

The tow car velocity was related to the interval of pulses sent to control motor rotation through Eq. 1. Since a driving pulley with 0.123 m of diameter was used and 200 pulses per run were selected in the driver, Eq. 1 results in Eq. 2 (estimated velocity). Thus, when the user started the system, the interval of pulses was calculated by the software and sent to the TCM, which accelerate the tow car until the desired velocity. At the end of the test, the program allowed saving all the information collected by the modules in text files, for subsequent utilization in the adjustment of the current meter equation.

$$v = \frac{\pi \cdot D}{n \cdot t} \tag{1}$$

$$v = 0.0019321t^{-1} \tag{2}$$

where:

v - estimated displacement velocity, m s^{-1};

D - diameter of the driving pulley, m;

n - number of pulses per run, dimensionless; and

t - time between pulses, s.

The tests were performed using the developed system, along with a vertical-axis (Pygmy) and a horizontal-axis (Miniature) current meter. The Pygmy model has a six-cone arrangement forming a symmetric, balanced structure. The Miniature has three different interchangeable propellers to be used according to the velocities, each of which was individually tested in the system.

Current meter velocities were tested until the limit of the motor, a point at which it did not move due to probable problems of torque and inertia. This velocity limit depends on the current meter model and on its propellers. For the tested models, the limits were around 2.15 m s^{-1} for the Pygmy and 2.5 m s^{-1} for the Miniature, i.e., until reaching a certain velocity at which the rotation velocity of the current meter exceeded the data-processing limit for which the DAM was projected, approximately 27 rps.

For both current meters and their propellers, characteristic linear regression equations were adjusted relating the displacement velocity to the propeller rotation velocity (Eq. 3) (Engel, 1999; Johnstone, 2008; Staubli & Hegland, 1982; Mattas & Ramešová, 2013). Previous studies using two linear equations for velocities higher and lower than 0.3 m s^{-1}, for the same current meter propellers, reported that for low velocities the linear equation is no longer adequate, and proposed an exponential model (Eq. 4) (Engel, 1999). In addition, this author also expanded this exponential equation in order to use it in all the measurement range of the device, substituting both linear equations, which is the reason why such model was also used to adjust the equations of the tested current meters, in order to compare it with the linear model.

$$v = a\omega + b \tag{3}$$

$$v = A\varpi + Be^{-k\omega} \tag{4}$$

where:

v - water velocity, m s^{-1};

ω - rotation velocity of the current meter propeller, rps;

a, b, A, B and k - calibration coefficients; and

e - Neper number.

Once obtained the results of the calibration test, the Root Mean Square Error (RMSE) (Eq. 5) was used as a reference value to decide on which calibration model should be recommended for the use in current meters. The model to be recommended is that with the lowest value of RMSE.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{o,i} - x_{e,i}\right)^2}{n}} \quad (5)$$

where:

$x_{o,i}$ - observed i value; and

$x_{e,i}$ - estimated i value.

Results and Discussion

The measurements of displacement velocity are important, since the velocities estimated by Eq. 2 not always correspond to the displacement velocities measured in the test (Hubbard et al., 2001). Thus, the relationship between estimated and measured velocities, for estimated velocities of up to 3.0 m s^{-1} is shown in Figure 2A.

For the vertical-axis current meter (Pygmy), the measured velocity corresponded to the estimated velocity until approximately 2 m s^{-1}, from which it did not increase with the increment in the estimated value. For the horizontal-axis current meter (Miniature), with the propellers 1, 2 and 3, this correspondence was maintained until approximately the estimated velocity of 2.5 m s^{-1}. The differences between the maximum velocities of each current meter are due to their different hydrodynamic resistances, which is lower for the Miniature, because it reaches higher velocity.

The deviation between measured and estimated velocities (relative difference) is due to the lower torque of the step motor at higher velocities (higher shaft rotation), which is not

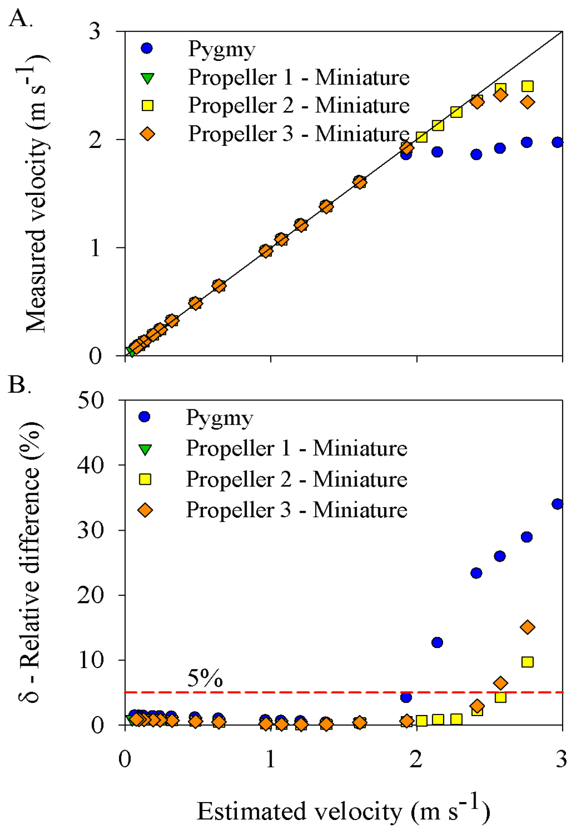


Figure 2. Relationship between estimated and measured velocities (A) and relative difference for the measured velocities (B)

sufficient to meet the inertia of the pulled set. The uniform movement was compromised, since the motor shaft locked when velocities higher than 2.15 m s^{-1} were required in the tests with the Pygmy current meter and higher than 2.5 m s^{-1} for the Miniature, preventing the carrying out of the tests. This guarantee of stability in the tow car movement is important for calibration tests, because it reflects in velocity measurements, thus influencing the adjustment of calibration equations.

These maximum velocities in the tests can still be considered as low, because, for some current meter models, the measurement range extends until approximately 10 m s^{-1} (Camnasio & Orsi, 2011). Two reasons may be attributed to this limitation in the developed system: its maximum traction capacity and the distance traveled by the current meter along the channel. Considering that distances of 5 m were necessary for acceleration and 2 m for slowdown, there were only 5 m left for the data collection required for calibration. One alternative would be the use of a motor operated by another principle, requiring smaller distances for acceleration-deceleration and also providing higher torque for the highest velocities. Such motor, however, must also show reliability and stability in the rotation velocity, similar to the step motor. As to the channel length, it limits velocities higher than 2.3 m s^{-1}, because a greater distance would be necessary for acceleration, decreasing the useful length for data acquisition by the DAM.

Analysing the correspondence between estimated and measured velocity (Figure 2A) in terms of relative difference (δ), Eq. 6, values lower than 5% were obtained at estimated velocities of approximately 1.85 m s^{-1} for the Pygmy current meter, 2.35 m s^{-1} for the propellers 1 and 2 of the Miniature and 2.45 m s^{-1} for the propeller 3. Therefore, for the subsequent adjustment of their calibration equations, the following criterion of relative difference was adopted as the validity limit of the equations.

$$\delta = \left(\frac{|v_e - v_o|}{v_e}\right) \quad (6)$$

where:

δ - relative difference, %;

v_e - estimated or adjusted velocity, m s^{-1}; and

v_o - measured velocity, m s^{-1}.

For the Pygmy model, the velocity measured during the tests and the respective rotation velocities are shown in Figure 3A, along with the adjusted linear (Eq. 3) and exponential (Eq. 4) equations and the original equation of the equipment, provided by the manufacturer.

Considering velocities lower than 0.2 m s^{-1}, the adjusted linear equation showed relative differences of up to 17.54% compared with the observed data (Figure 3B), while for the exponential equation the highest value was 6.53%. For the entire range tested, the original equation underestimated velocity values; thus, it showed the highest relative difference compared with the other adjusted equations and its highest value was 34.25%, for the lowest velocity, 0.07 m s^{-1}. This result reinforces the need for periodic calibration of current meters, as suggested by Camnasio & Orsi (2011) and USDI (2001).

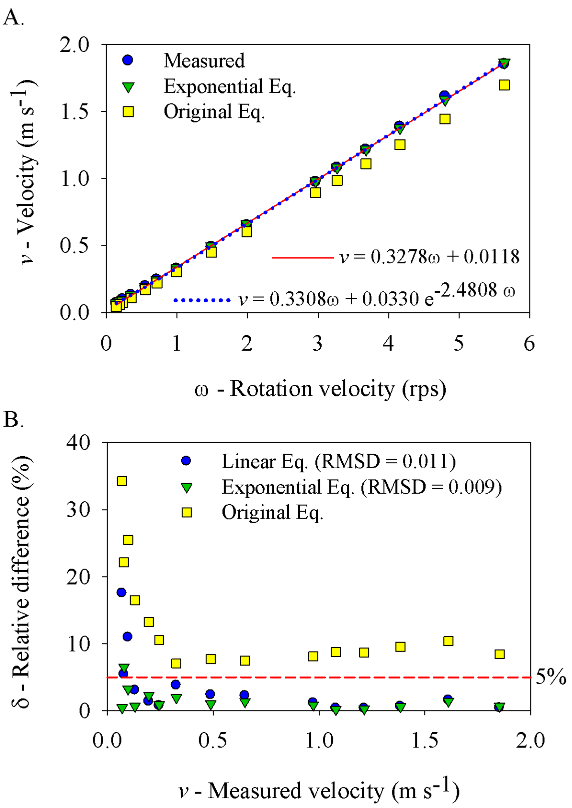


Figure 3. (A) Equations of the Pygmy current meter and (B) Relative differences, δ

The highest relative differences were obtained for low velocities, for both current meter models (Figures 3 and 4). The exponential equation was expected to show a better adjustment for the range of low velocities (Engel, 1999); however, for the tested models of current meter, the estimates were close to those obtained by the adjusted linear equation. At low velocities, the propeller rotation velocity is low, being close to a static zone when it no longer shows movements. This zone corresponds to 0.07 m s^{-1} for the Pygmy model. Thus, in this range, the estimates showed higher difference than in the rest of the measurement range, and the friction between the components of the current meter was the main factor of influence (Newman & Bennell, 2002).

This discrepancy at low velocities was also mentioned by Carter & Anderson (1963), who tested two current meters with up to 48 observations for velocities of 0.08 m s^{-1}, 24 for 0.15 and 0.23 m s^{-1} and 20 for 0.34 and 0.46 m s^{-1}. For the lowest velocity and even with the higher number of replicates, these authors reported a coefficient of variation of 1.76% for one current meter and 2.77% for the other, while for the highest velocity these values decreased to 0.64 and 0.59%, respectively. Relative differences lower than 1% for linear calibration equations of two current meters in the estimates of velocity were reported by De Doncker et al. (2008) for velocities of up to 0.583 m s^{-1} for one model and 1.051 m s^{-1} for another. These authors also obtained higher values of relative difference for velocities

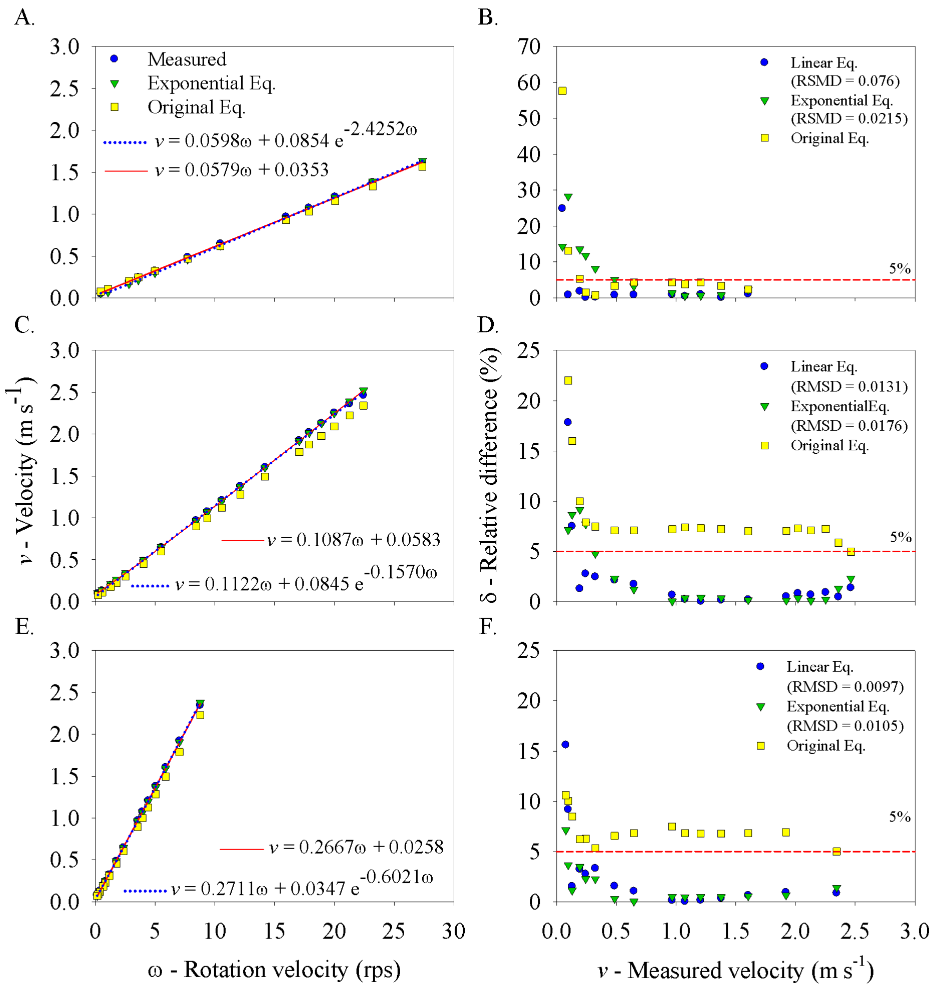


Figure 4. Equations for the Miniature current meter and the respective relative differences, δ: (A) and (B) - propeller 1, (C) and (D) - propeller 2 and (E) and (F) - propeller 3

Table 1. Current meter equations obtained in the tests and their respective measurement ranges

Model		Original equation provided by the manufacturer	Equation obtained in the developed system	Measurement range (m s^{-1})	
				δ < 5%	δ < 1%
Pygmy		v = 0.3000w + 0.0040	v = 0.3278w + 0.0118	0.13 to 1.00	1.00 to 1.85
Miniature:	Propeller 1	v = 0.0560w + 0.0330	v = 0.0579w + 0.0353	0.10 to 0.25	0.25 to 1.60
	Propeller 2	v = 0.1030w + 0.0300	v = 0.1087w + 0.0583	0.20 to 0.90	0.90 to 2.35
	Propeller 3	v = 0.2535w + 0.0040	v = 0.2667w + 0.0258	0.13 to 0.90	0.90 to 2.45

lower than 0.3 m s^{-1}, and lower values for higher velocities, as observed in the tests, suggesting the use of equations for velocities higher than half the measurement range. In tests conducted by Hubbard et al. (2001) with vertical- and horizontal-axis current meters, with velocities from 0.076 to 2.44 m s^{-1}, the original equation also underestimated the observed values between 0.4 and 0.7%, on average, for velocities above 0.3 m s^{-1}, and between 0.5 and 1.0% for lower velocities.

For the Miniature current meter, the relative difference of the equations also showed the same behavior of the Pygmy model, with higher values for the lower velocities (Figures 4A, C and E). The highest values of relative difference for the linear equation were 24.82% for the propeller 1, 17.81% for the propeller 2 and 15.59% for the propeller 3 (Figures 4B, D and F). For the exponential equation, the relative differences were 28.25, 9.16 and 7.14% for the same propellers, respectively. These relative differences occur at velocities lower than 0.3 m s^{-1}, which is a region where equations do not show a reasonable adjustment (Engel, 1999), even the exponential equation, recommended for this case.

For velocities higher than 0.3 m s^{-1}, both equations, linear and exponential, showed relative differences lower than 5% in relation to the observed value (Figures 4B, D and F). On the other hand, the original equation remained below this value only for the propeller 1 and for the point of highest velocity with the propellers 2 and 3. Therefore, the original equations of each propeller in the Miniature current meter did not meet the criterion of relative difference lower than 5% between the estimated and the observed value, as also occurred for the Pygmy model.

The equation of the propeller 1 of the Miniature current meter could only be obtained until the velocity of 1.6 m s^{-1} (Figure 4A) since the DAM was projected for the acquisition of rotation velocities of up to 27 rps. From this value on, the module no longer responded, due to limitations of hardware.

In the use of the current meter at the field, besides the difficulty of operating the device at high velocities, its circuits can show limitations in recording the rotation velocity (Newman & Bennell, 2002). Therefore, the tests of the various devices in a calibration system, considering the different existing manufacturers, will always have some complication (Baker et al., 2013), especially the interface between device and software. Some current meter models have an electronic circuit to process the signal from the propeller, especially the most modern ones, which can be used in combination with the DAM, in case it provides an output signal suitable to be acquired by this module. This acquisition module presented itself as a solution with easy use, which can also be employed in current meters in which the output signal is a tension pulse, allowing the improvement of a range of equipment considered so far as obsolete, because the current models offer a series of resources to the user. In addition, this module can be a solution for the continuous monitoring of velocity in water streams for hydrological studies, as in obtaining the parameters of key-curves, for instance.

After the calibration routine of the current meters evaluated in this study, Table 1 shows the equations and measurement ranges recommended for the use of the instruments. The equations indicated for each one of the current meters were selected according to the lowest values of RMSE.

Conclusions

1. The developed system showed reliability in the tests for both current meter movement and data acquisition.
2. Measuring the current meter velocity in each movement allowed obtaining the limits of the system in relation to the velocity estimated for each current meter model.
3. The developed Data-Acquisition Module allowed performing tests using current meters with propeller rotation of up to 27 rps, allowing testing current meters until this limit .
4. The original equations of current meter propellers must be substituted by the new equations obtained, because their estimates do not correspond to the measured velocities.

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